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(54) Title: OPTO-ELECTRONIC ROTARY ENCODER
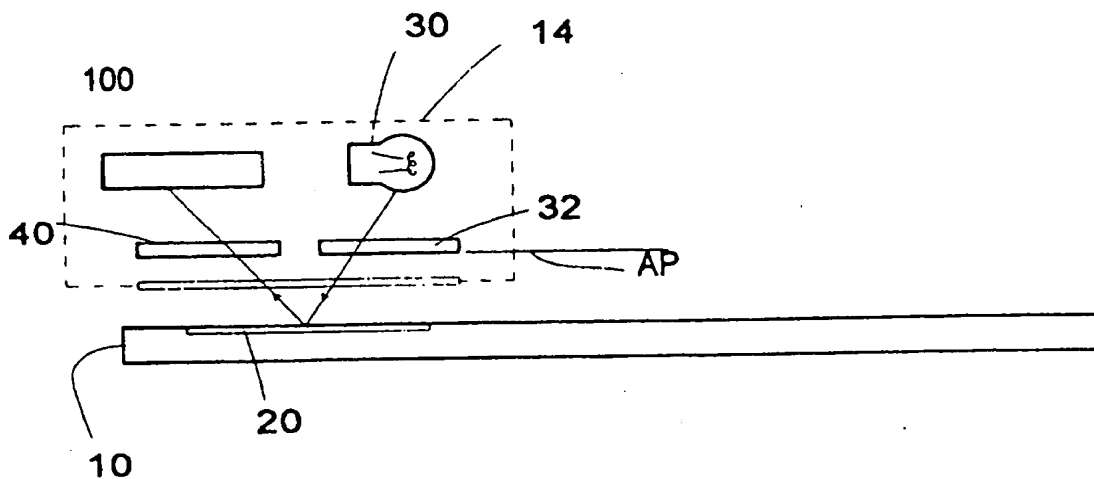
(57) Abstract

A rotary encoder has a scale (22) which rotates relative to a pair of readheads (14). Each of the readheads projects light onto the scale and generates at an analyser grating (40), a periodic light pattern, such as interference fringes. The interference fringes and the analyser grating interact to produce a series of resultant Vernier fringes which are incident upon a structure detector array (100). In one embodiment the analyser grating is configured to interact with the angularly extending interference fringes to generate linear resultant fringes. It has been found that phase errors due to eccentric rotation of the scale (22) reduce with decreasing pitch of the resultant fringes.

OPTO-ELECTRONIC ROTARY ENCODER

The present invention relates to an opto-electronic rotary
encoder which may be employed, for example, to measure
angular displacement of one rotatable body relative to
another.

Such rotary encoders are known per se, and typically
include a code wheel, mounted to a first one of the
relatively rotatable bodies, having a plurality of radially
extending, circumferentially spaced lines, situated at
equi-angular intervals about the periphery of the code
wheel, thereby to form a scale. An optical readhead,
mounted to the other of the relatively rotatable bodies,
and in register with the scale, projects light onto the
scale which, depending upon the configuration of code
wheel, is then either reflected or transmitted. From the
reflected or transmitted light, the readhead generates a
series of signals which may be used to generate an
incremental count indicative of the relative angular
displacement of the first and second relatively rotatable
bodies.

A first aspect of the present invention provides opto-
electronic encoder apparatus for measuring relative
movement having a scale defined by a series of spaced apart
lines, and a readhead lying in register with the scale, the
scale and readhead being relatively movable in the
direction of spacing of the lines; the readhead comprising:
        means for illuminating the scale whereby light passed
on by the scale forms a periodic light pattern;
        an analyser grating for interacting with said periodic
light pattern to generate a resultant fringe pattern; and
        a detector upon which said resultant fringe pattern is
incident, for generating a plurality of phase shifted
cyclically modulating signals upon said relative movement;
        wherein one of the periodic light pattern and
resultant fringe pattern is a linear pattern, and the other

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is an angular pattern.

An independent aspect of the present invention provides
opto-electronic rotary encoder apparatus for measuring
5   relative angular displacement having a scale defined by a
series of spaced apart lines, and a readhead lying in
register with the scale, the scale and readhead being
relatively movable in the direction of spacing of the
lines; the readhead comprising:
10   means for illuminating the scale whereby light passed
on by the scale forms a periodic light pattern;
          an analyser grating for interacting with said periodic
light pattern to generate a resultant fringe pattern; and
          a detector upon which said resultant fringe pattern is
15   incident, for generating a plurality of phase shifted
cyclically modulating signals upon said relative movement,
comprising:
          a plurality of sets of photosensitive elements spaced
apart in the direction of spacing of said resultant
20   fringes, elements of different sets being interleaved in a
repeating pattern, and all elements of a given set being
electrically connected in common, wherein adjacent elements
are separated by a distance not equal to the fringe pitch
of said resultant fringes.
25

Embodiments of the invention will now be described, by way
of example, and with reference to the accompanying drawings
in which:
          Fig 1 is a schematic elevation of a rotary encoder in
30   accordance with the present invention;
          Fig 2 is a side view on II-II in Fig 1;
          Figs 3a-c are signal diagrams illustrating the
generation of resultant fringes;
          Fig 4 is a vector diagram;
35   Fig 5 is an elevation of the detector array in the
readhead of Fig 2;
          Figs 6a-c illustrate the effect of code wheel
eccentricity;

Fig 7 is a graph showing phase error due to
eccentricity;

Fig 8 illustrates the interference fringe pattern
generated in the readhead of Fig 2;

5   Fig 9 is an elevation of a part of a modified analyser
grating; and

Fig 10 is an elevation of a detector array used with
the analyser of Fig 9.

10   Referring now to Figs 1 and 2, an angular encoder for
measuring relative angular displacement of two members
includes a circular code wheel 10, mounted to one of the
members in a manner permitting rotation about a central
bearing 12, and a pair of opto-electronic readheads 14,

15   mounted to the other of the members. The code wheel 10
has, at its periphery, a rotary scale 20, made up of a
series of alternately light-reflecting and non-reflecting
lines 22; the lines 22 extend radially and are
circumferentially spaced from each other. Alternatively,

20   the lines may be provided by a phase grating (known per se)
type structure, etched into the surface of the code wheel
10 to generate a scale.

The readheads 14 each include a diffuse light source 30,
25   which generates a collimated beam that illuminates the
scale 20 via an index grating 32. The index grating 32
comprises alternate light transmitting and opaque lines
(not shown), whose angular pitch and circumferential
spacing are identical to the portion of the lines 22 of the

30   scale 20 with which the window defined by the index grating
32 is in register. After passing through index grating 32,
light is reflected from the scale 20 and, by virtue of its
interaction with both index grating 32 and scale 20, a
periodic light pattern in the form of interference fringes

35   is formed in an analyser plane AP. The angular of both the
lines on the index grating 32 and the scale 20, together
with the stand-off distance between grating 32, and scale
20 are chosen so that a corresponding optical mechanism to

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the linear encoding mechanism shown in GB 1504691, applies.
In accordance with this type of optical mechanism, the
interference fringes formed in the analyser plane AP will
have the same angular pitch as the lines of the index
5   grating 32 and scale 20 (N.B. in an alternative optical
mechanism shadow fringes may be formed).

Rotation of the code wheel 10 relative to the readhead 14
will cause rotation of the interference fringes generated
10   in the analyser plane AP, and a corresponding cyclically
varying modulation of the intensity of light incident upon
any given point in the said plane. Observation of two or
more phases of this light intensity modulation will enable
the determination of both the direction and magnitude of
15   angular displacement of the wheel 10. However, direct
observation of this light intensity modulation is only
possible with a photo voltaic transducer whose dimensions
are less than or equal to one half of the width of an
interference fringe. In the present example, the linear
20   spacing between adjacent lines of the scale 22 at their
outer radius is equal to 2 microns, and this is therefore
also the maximum linear spacing between adjacent fringes of
the corresponding interference fringe pattern generated in
analyser plane AP. It is therefore not practicable or cost
25   efficient to construct photodetectors of the requisite size
in order to monitor directly the aforementioned light
intensity modulation. To make the light intensity
modulation manifest to a photo voltaic transducer whose
dimensions are substantially larger than the pitch of the
30   interference fringes, an analyser grating 40 is provided in
the analyser plane AP.

The function of the analyser grating 40 will now be
explained with reference to Figs 3a-c. Referring now to
35   Fig 3a, the light intensity distribution of the
interference fringes 50 with angle is illustrated in Fig
3a. It can be seen that the intensity distribution is
substantially sinusoidal, and that the angular pitch of the

5

fringes is constant. The configuration of the analyser
grating 40 is illustrated in juxtaposition with the fringes
50 in Fig 3b. It can be seen from Figs 3a and 3b that the
angular pitch of the analyser grating 40 is constant, but

5   the juxtaposition of the grating 40 with the interference
fringes 50 reveals that the angular pitch of the grating is
fractionally larger than that of the fringes; the fringes
having an angular spatial frequency of 12 peaks for the
angular displacement of α°, while the lines of the analyser

10   grating 40 having an angular frequency of 11 lines per
angular displacement α°. As a result, when the
interference fringes 50 are incident upon the analyser
grating 40, what is observed from the side of the grating
40 remote from the scale 20 is a resultant fringe 60. The

15   generation of the resultant fringe 60 may be explained in
that at the central portion of the illustrated part of the
analyser grating 40 the high intensity peaks of the
interference fringe pattern lie in register with non-
transmissive lines of the grating 40, and so comparatively

20   little of the incident light from the interference fringes
50 is transmitted by the analyser grating 40. Toward the
periphery, the high intensity peaks lie increasingly in
register with light transmissive lines of the grating 40,
as a result of which, more light is transmitted by the

25   analyser grating 40. The generation of a resultant fringe
60 of this type may be likened to the generation of a beat
frequency, or to a Vernier scale. For this reason,
resultant fringe 60 may be referred to as a resultant
Vernier fringe.

30

Rotational movement of the interference fringe pattern
relative to the analyser grating 40 (upon rotation of the
code wheel 10) by an angular displacement equal to one
interference fringe pitch, will result in a corresponding

35   shift of the resultant Vernier fringe by one resultant
fringe pitch. It is therefore valid to observe the light
intensity modulation occurring downbeam of the analyser
grating from the shift of the resultant Vernier fringe 60

as a method of determining the angular displacement of the
code wheel, since the shift of the resultant Vernier
fringes 60 has a one-to-one relationship with the shift of
the interference fringes 50.

5

Movement of the resultant Vernier fringes is detected by a
structured array 100 of the type shown in Fig 5, comprising
a semiconductor substrate 102, upon which a series of
photosensitive elements are formed. The elements 110

10 extend radially with respect to the code wheel, and are
grouped into three sets 110A,110B,110C, with all elements
of a given set being electrically connected in common. The
elements 110 are interleaved in a repeating pattern 110A-
110B-110C, and are angularly spaced such that consecutive

15 like elements are separated by an angle $1/V_f$ equal to the
pitch of a resultant Vernier fringe. As the resultant
Vernier fringes move across the array, each set of elements
110 will generate a sinusoidally varying electrical output;
the outputs of the three sets of elements 110A,110B,110C,

20 having a phase relationship of 0°,120°, and 240°
respectively may then be combined in a known manner, to
produce a pair of sinusoidally varying quadrature outputs,
yielding the magnitude and direction of rotation of the
code wheel.

25

The pitch of a resultant Vernier fringe generated by the
interaction between an incident interference fringe pattern
and an analyser grating can be calculated in advance by
means of simple vector mathematics. Referring now to Fig

30 4, a vector I_f represents the number of fringes per unit
angular displacement of the incident interference fringe
pattern; the vector A_g indicates the number of lines per
unit angular displacement of the analyser grating; and the
vector V_f denotes the number of resultant Vernier fringes

35 per unit angular displacement which will be generated as a
result of interaction between the incident interference
fringes and the lines of the analyser grating. The sum of
these three vectors must be equal to zero. Thus, for

example, if the incident interference fringe pattern has
250 fringes per unit of angular displacement, and the
analyser grating has 249 lines per unit of angular
displacement, there will be only 1 resultant Vernier fringe
5   per unit of angular displacement. Thus it can be seen that
the mathematics correspond to the calculation of the
generation of a beat frequency between two interacting
signals.

10   The pitch of the interference fringes, the pitch of the
lines on the analyser grating and the pitch of the
resultant Vernier fringes are $1/I_f$, I/A_g, I/V_f respectively,
and are angles. A further way to describe pitch in an
angular encoder is in terms of circumferential spacing
15   between adjacent lines or fringes, and this is given by the
expression

$$2\pi\frac{R}{N}$$

where

R is the radius (measured from the point from which the
20   lines or fringes extend radially) at which the lines or
fringes are being viewed; and

N is the number of lines or fringes per revolution.

25   The circumferential spacing is a significant parameter
because although the apparatus described thus far has a
code wheel 10 whose scale 20 is mounted with perfect
concentricity, in practice it is likely that the mounting
of the code wheel 10 will be eccentric. The effect of such
30   an eccentric mounting is a change in the circumferential
spacing of the scale lines with rotation of the code wheel,
when viewed from the readhead. Referring now to Fig 6a,
the position of the optical centre O of the code wheel 10
(i.e. the point from which all the scale lines extend
35   radially) is illustrated relative to the mechanical centre

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M about which the code wheel 10 rotates. The eccentricity
of the scale 20 is equal to the distance between the two
points and is designated as e. Referring to Figs 6b, the
readhead 14 is mounted relative to the code wheel 10 so
5   that at a first angular displacement of the code wheel 10
the circumferential spacing of the part of the scale with
which the readhead is in register is

$$2\pi\frac{r}{N}$$

where
10

r is the mean scale radius.

Referring to Fig 6c a 180° rotation of the code wheel 10
from this angular displacement will result in a change in
15   the circumferential spacing (when taking into account the
doubling effect of reflection) of the scale which lies in
register with the readhead to:

$$2\pi\frac{(r-2e)}{N}$$

This change in the circumferential spacing of the scale 20
20   will cause a corresponding change in the circumferential
spacing of the interference fringes incident upon the
analyser grating, and consequently, a change in the
circumferential spacing of the resultant Vernier fringes
incident upon the photosensitive array 100. Because the
25   circumferential spacing between consecutive like elements
110 of the array 100 is chosen to match the circumferential
spacing of the resultant Vernier fringes, a change in the
circumferential spacing of the resultant Vernier fringes
from that selected for the elements 110 of the array 100
30   will give rise to a phase error in the electrical outputs
of the array 100. If there are n photosensitive elements
110 in each set 110A,B,C of elements, and w is the

circumferential distance (see Fig 5) across the array 100,
then the required circumferential spacing of the resultant
Vernier fringes is:

$$\frac{w}{n}$$

using the vector analysis described above it can be shown
that the new circumferential spacing q of the resultant
Vernier fringes following the change in circumferential
spacing of the scale is equal to

$$q = \frac{1}{\dfrac{N}{2n(R-2e)} - \dfrac{N}{2nR} + \dfrac{n}{w}}$$

The percentage phase error x arising from this change in
circumferential spacing of 1 resultant Vernier fringe is

$$x = \left| \frac{w/n - q}{w/n} \right| \times 100$$

Summing for all fringes across the array, the accumulative
error A is

$$A = (x + 2x + 3x + 4x + \ldots nx)/n$$

$$A = (n+1)x/2$$

It can be seen that for a given value of e both the
absolute and percentage change in circumferential spacing
of resultant Vernier fringes is smaller with increasing n.
Thus, the greater the number of resultant Vernier fringes
(i.e. the smaller the circumferential spacing of the

resultant fringes), the lower the phase error. Fig 7 is a
graphical illustration of the change in phase error with
increasing number of resultant Vernier fringes, for a 10μm
value of eccentricity and a scale of mean radius of 35.5mm
5   having 55800 lines per rev.

Qualitatively this phenomenon may be understood in that
small pitch resultant Vernier fringes are produced when the
circumferential spacings of the interference fringes (and
10   thus the scale) and analyser grating differ by a relatively
large amount. The larger this difference is, the smaller
the effect proportionally of a change in the
circumferential spacing of the scale (and thus the
interference fringes) due to eccentricity.
15

Referring now to Fig 8, the interference fringes incident
upon the window 200 defining the extent of the analyser
grating are illustrated.

20   We have appreciated that because the geometry of the
analyser grating 40 with which the inference fringes
interact determines the size of the resultant Vernier
fringes, it is possible to configure the analyser grating
40 to obtain any pitch and/or geometry of resultant fringes
25   from any given incident fringes (i.e. in the examples
described herein, interference fringes). For example, a
parallel, or "linear" resultant Vernier fringe pattern may
be generated from angular radially extending fringe pattern
or vice versa.
30

To obtain n parallel resultant Vernier fringes across the
total width w of the analyser grating 40, the configuration
of the analyser grating 40 may be determined in the
following way:
35

The linear pitch of the 1st interference fringe from
the 0th fringe (0th fringe extending substantially
perpendicular to the window 200 defining the boundaries of

the analyser grating 40) at its inner radius within window
200 is P_i.

5   The number of lines per unit displacement (i.e. the spatial
frequency) of lines at this pitch is thus given by $1/P_i$.

The required spatial frequency of resultant Vernier fringes
is n fringes across an analyser window 200 of width w, i.e.

10   n/w.

Referring to Fig 9, the requisite linear pitch between the
0th and 1st line of the analyser grating at the inner
radius of the analyser grating window 200 required to
15   generate a resultant Vernier fringe of width W/N is A_i,
corresponding to a spatial frequency of $1/A_i$.

Using the vector analysis described above,

20       $1/A_i = 1/P_i - n/w$

     rearranging

     $A_i = wP_i/(w-nP_i)$
25

In order that the resultant Vernier fringes are made to
extend parallel to each other, the pitch A_o between the 1st
and 0th line of the analyser gating at its <u>outer</u> radius
30   within window 200 must be such that it will also interact
with the interference fringe to produce a resultant Vernier
fringe of pitch w/n. The same calculation must therefore
be repeated in respect of the 1st and 0th interference
fringe to generate a value A_o of pitch at the outer radius
35   of 1st and 0th lines of the analyser grating.

Thus,

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$$A_o = wP_o/(w-nP_o)$$

Where P_o is the pitch between the 0th and 1st fringes at the
outer radius.

5

These calculations are then reiterated in respect of all
further lines of the analyser grating, and the entire
grating may then be generated by mirroring the resulting
10   configuration about an axis of symmetry defined by the 0th
line.

A suitably structured photodetector array 400, configured
to generate three phase-shifted cyclically modulating
15   electrical signals corresponding to the light intensity
modulation of the linear resultant Vernier fringes upon
rotation of the code wheel 10 is illustrated in Fig 10.   As
previously the detector array 400 comprises a semi-
conductor substrate 402, having provided thereon a
20   plurality of elongate substantially parallel light
sensitive elements 410, grouped into three sets
410A,410B,410C, with all elements of a given set being
connected electrically in common, and with the elements
being interleaved in a repeating pattern 410A-410B-410C.
25

The configuration of a modified or "distorted" analyser
grating to generate what in this specific example are
parallel resultant Vernier fringes is advantageous because
it enables a single design of photodetector array to be
30   made for both linear and angular encoders.   However, an
independent advantage is that, even in the case of an
angularly structured photodetector array, changes in e.g.
pitch or configuration of the index grating or scale may be
accommodated without modifying the structure of the array;
35   this greatly reduces the cost of modifying the encoder,
since a large part of the design cost involves the design
of the photodetector array.

CLAIMS

1.   Opto-electronic encoder apparatus for measuring
relative movement having a scale defined by a series of
spaced apart lines, and a readhead lying in register with
the scale, the scale and readhead being relatively movable
in the direction of spacing of the lines; the readhead
comprising:
           means for illuminating the scale whereby light passed
on by the scale forms a periodic light pattern;
           an analyser grating for interacting with said periodic
light pattern to generate a resultant fringe pattern; and
           a detector upon which said resultant fringe pattern is
incident, for generating a plurality of phase shifted
cyclically modulating signals upon said relative movement;
           wherein one of the periodic light pattern and
resultant fringe pattern is a linear pattern, and the other
is an angular pattern.

2.   Apparatus according to claim 1, wherein said scale is
a rotary scale.

3.   Apparatus according to claim 1, wherein said scale is
a linear scale.

4.   Apparatus according to any one of the preceding
claims, wherein said periodic light pattern is provided by
interference fringes.

5.   Apparatus according to claim 4, wherein said readhead
includes a coherent light source for illuminating the
scale.

6.   Apparatus according to claim 4, wherein said readhead
includes a diffuse light source and an index grating for
illuminating the scale.

7.   Apparatus according to any one of the preceding claims

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wherein said detector comprises a plurality of sets of
photosensitive elements spaced apart in the direction of
spacing of said resultant fringes, elements of different
sets being interleaved in a repeating pattern, and all
5   elements of a given set being electrically connected in
common, wherein adjacent elements are separated by a
distance not equal to the fringe pitch of said resultant
fringes.

10   8.   Opto-electronic rotary encoder apparatus for measuring
relative angular displacement having a scale defined by a
series of spaced apart lines, and a readhead lying in
register with the scale, the scale and readhead being
relatively movable in the direction of spacing of the
15   lines; the readhead comprising:
        means for illuminating the scale whereby light passed
on by the scale forms a periodic light pattern;
        an analyser grating for interacting with said periodic
light pattern to generate a resultant fringe pattern; and
20   a detector upon which said resultant fringe pattern is
incident, for generating a plurality of phase shifted
cyclically modulating signals upon said relative movement,
comprising:
        a plurality of sets of photosensitive elements spaced
25   apart in the direction of spacing of said resultant
fringes, elements of different sets being interleaved in a
repeating pattern, and all elements of a given set being
electrically connected in common, wherein adjacent elements
are separated by a distance not equal to the fringe pitch
30   of said resultant fringes.

9.   Apparatus according to claim 8, wherein said resultant
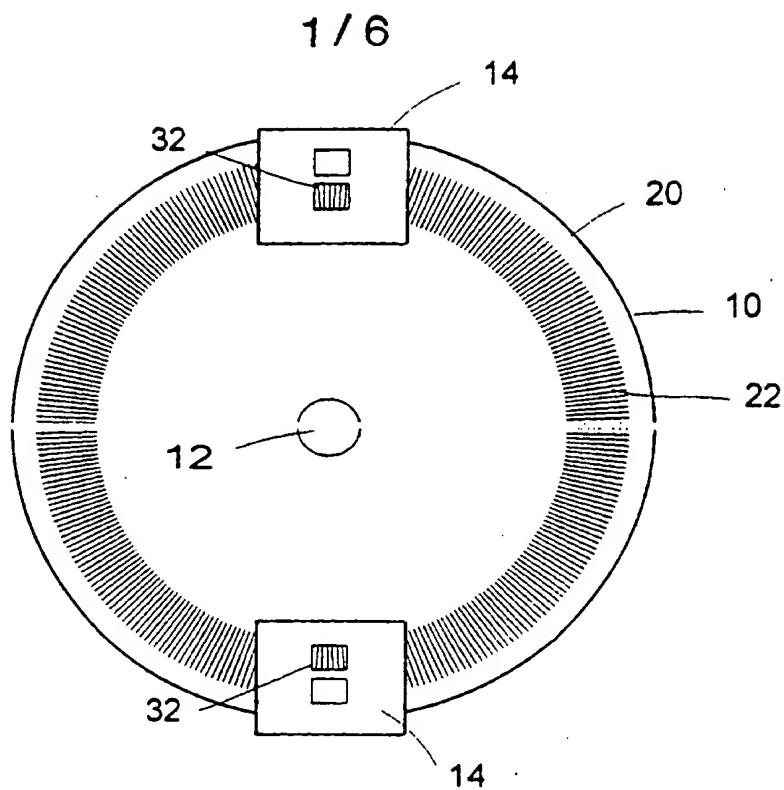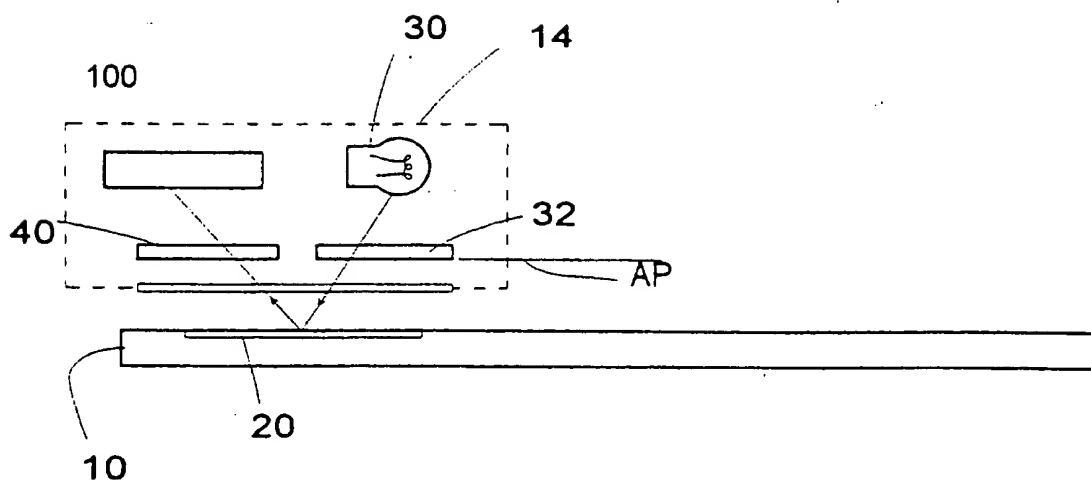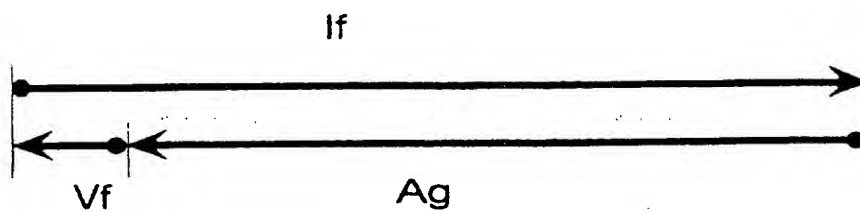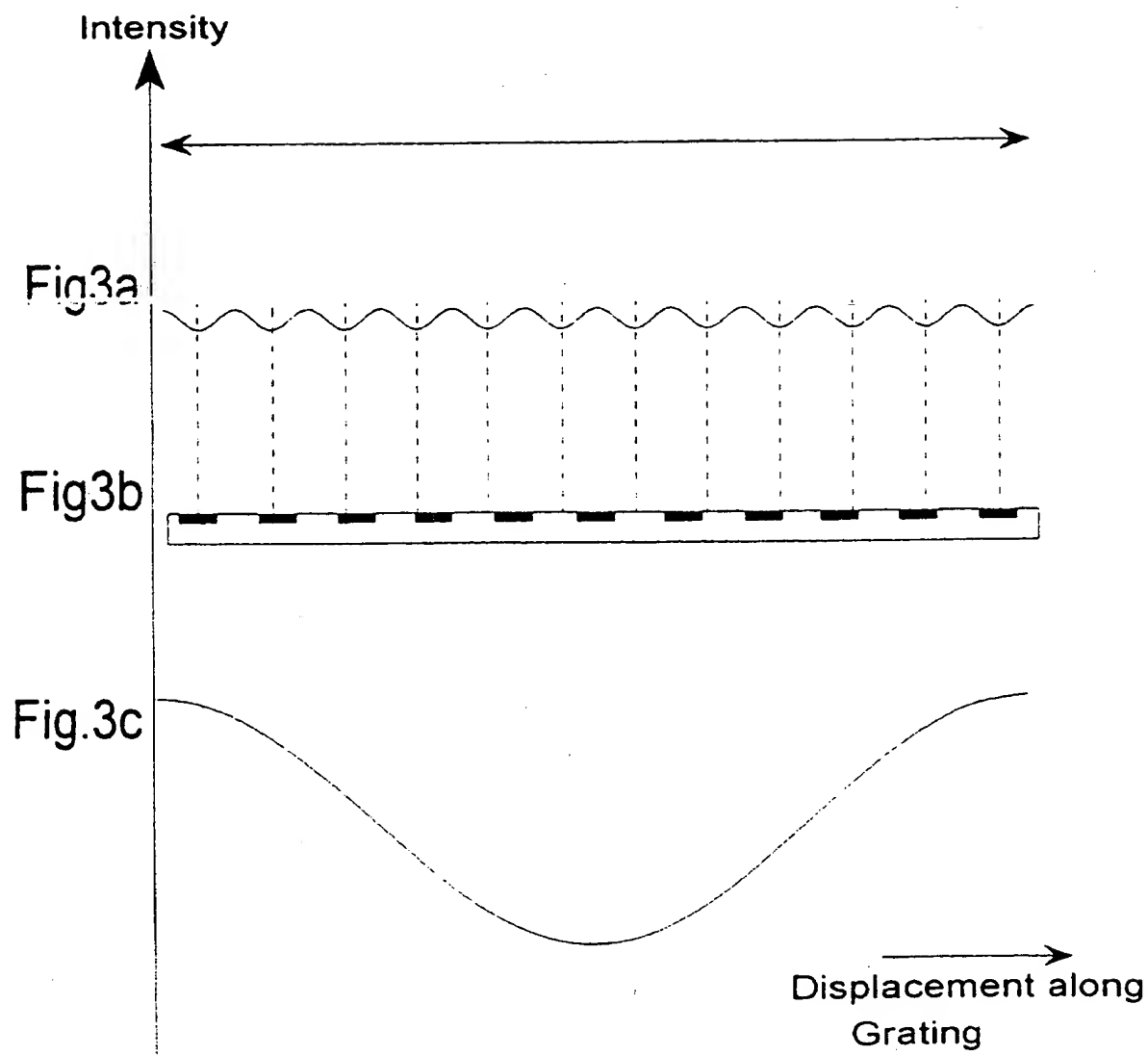fringes are linear fringes.

Fig.1

Fig.2

Intensity

Fig3a

Fig3b

Fig.3c

Displacement along
Grating

If

Vf

Ag

Fig.4
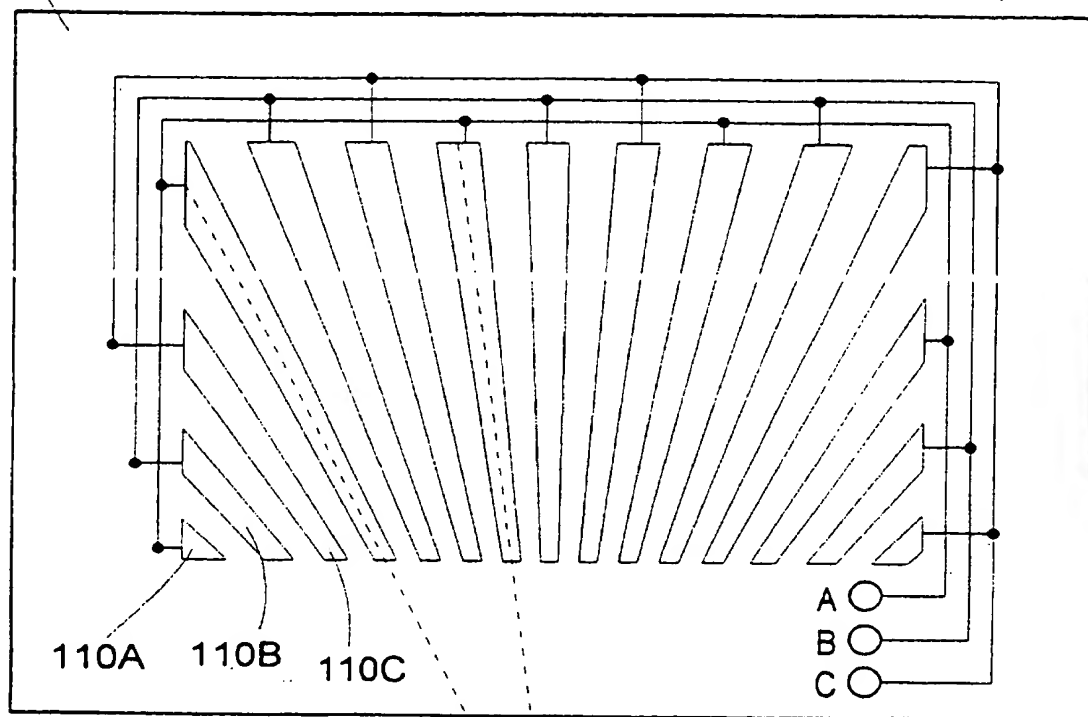
Fig.5

Fig.6a   Fig.6b   Fig.6c
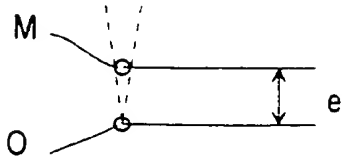
Fig.7.

% ERROR DUE TO ECCENTRICITY (10 MICRONS)
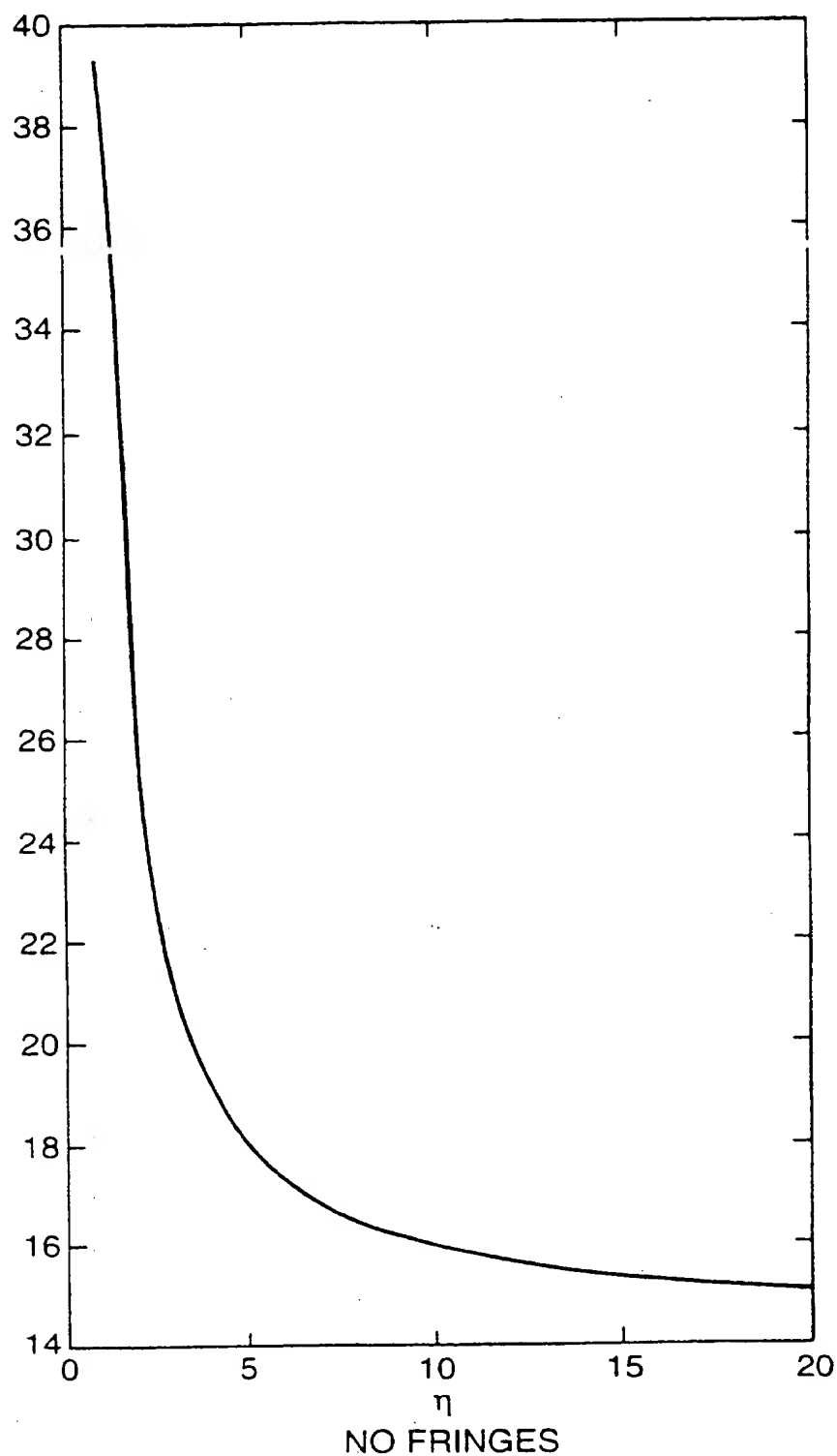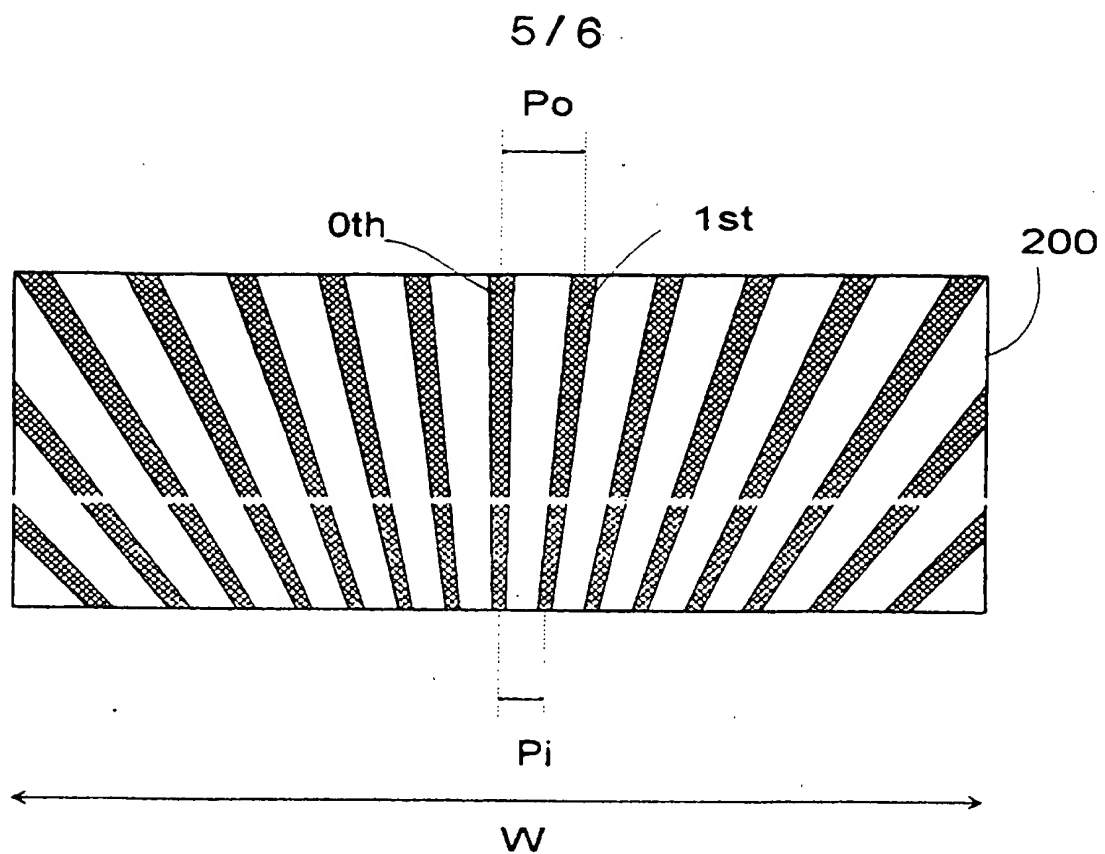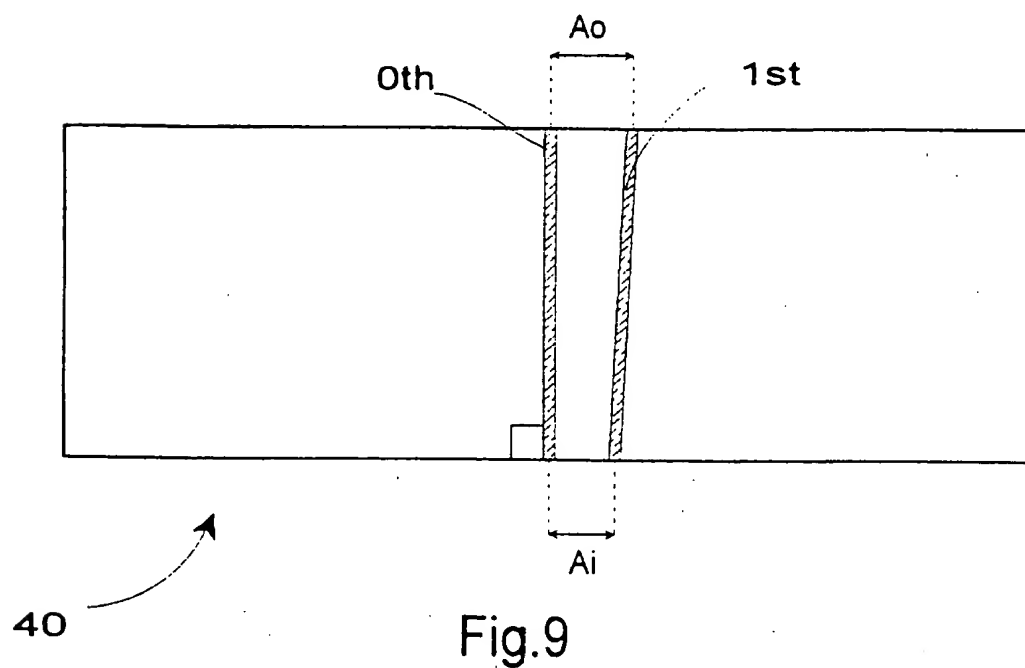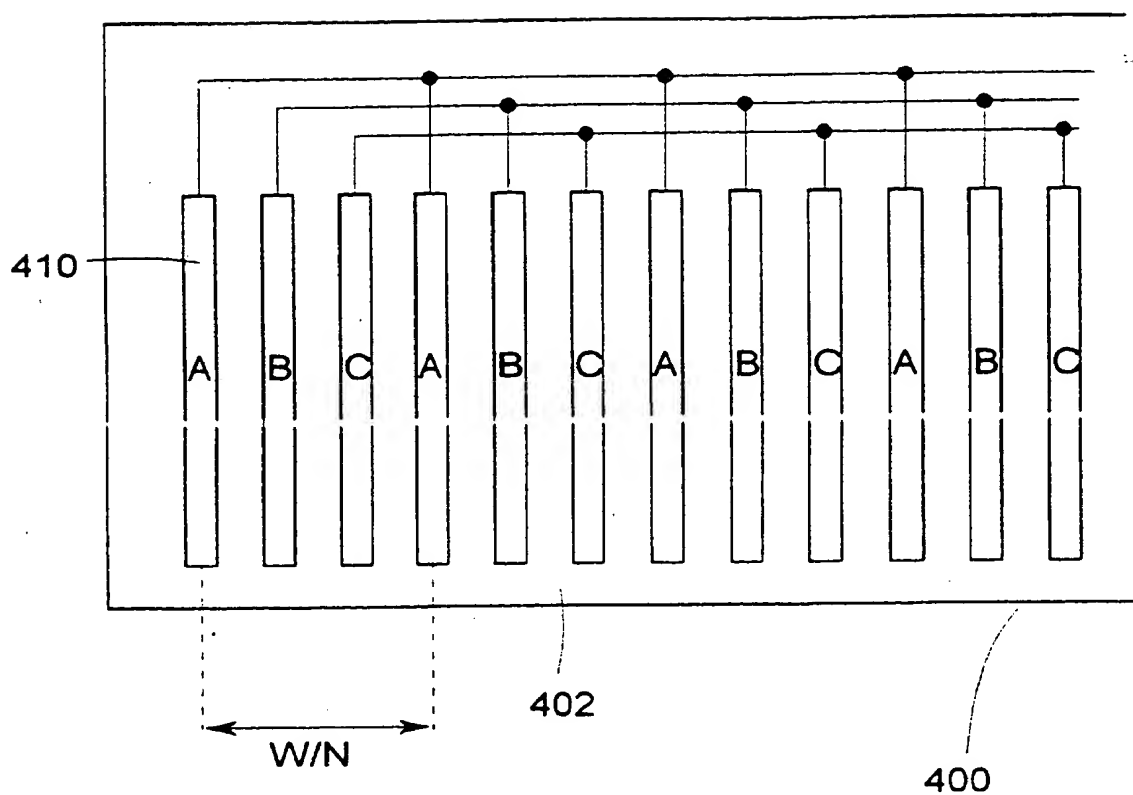
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NO FRINGES

Fig.8

Fig.9

Fig.10

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   G01D5/34   G01D5/38

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   G01D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 543 513 A (RENISHAW TRANSDUCER SYST) 26 May 1993 see the whole document	1
A	GB 1 220 094 A (CONTRAVES AG) 20 January 1971 see the whole document	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

    1. claims 1-7: use of a modified or "distorted" analyser grating to generate
                   linear resultant fringes from an angular periodic light pattern
    2. claims 8,9: using a plurality of interleaved photosensitive element sets in
                   connection with an angular encoder

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searches without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

    1-7

Remark on Protest ☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet (1)) (July 1992)

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